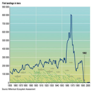
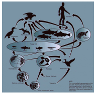
Sustainability, optimality, viability and other management criteria

3Days MESSH Brest 2024

Luc Doyen & Ivar Ekeland



Sustainability ?

- Balance present and future: intergenerational equity

  Rawls (1971), Solow (1974), Cairns & Long (2006)

- Balance ecological, social, economic goals:

triple bottom line

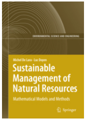
SUSTAINABLE DEVELOPMENT GOALS

- Intragenerational equity
- Issues: strong vers weak sustainability

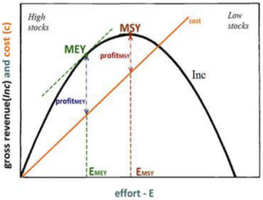
Neumayer, 2003

Substitutability - Aggregation ??

Models of sustainability for biodiversity

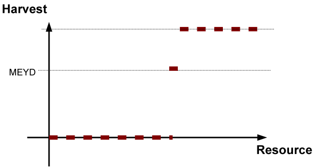


Equilibria
Gordon-Schaefer, 1954



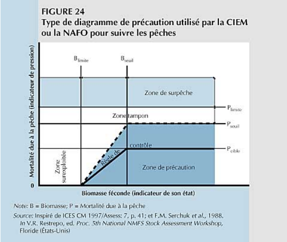
MSY ⟷ MEY

Optimal (intertemporal) control
Clark, 1976



Discounted Cost-Benefit, Welfare, Utility

Safety approaches
ICES precautionary



Steady state-control approach: MSY - MEY

- Dynamics (discrete time) with harvest (Shaefer):

$$x(t+1) = x(t) + G(x(t)) - qe(t)x(t)$$

- Example Logistic: $G(x) = rx(1 - \frac{x}{k})$

- Equilibrium $x(t+1) = x(t)$ in terms of effort:

$$e(x) = \frac{r}{q}\left(1 - \frac{x}{k}\right)$$

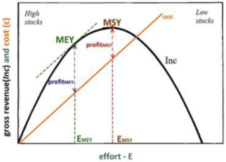
- Sustainable stock and harvest: If $e \leq r/q$,

$$x(e) = k\left(1 - \frac{qe}{r}\right), \quad h(e) = qex(e) = qek\left(1 - \frac{qe}{r}\right)$$

Strategy Maximum Sustainable Yield (MSY)

- Viewpoint of demand and consumer
- Optimal catch at equilibrium:

$$\max_{e \geq 0} h(e)$$



- Logistic:

$$e_{\mathrm{MSY}} = \frac{r}{2q}, \; x_{\mathrm{MSY}} = \frac{k}{2}, \; h_{\mathrm{MSY}} = \frac{rk}{4}$$

- Stock said biologically overexploited if $e > e_{\mathrm{MSY}}$

Strategy Maximum Economic Yield (MEY)

- Viewpoint of producer (fishermen)
- Rent

$$\pi(t) = ph(t) - ce(t)$$

where p price, c cost of effort

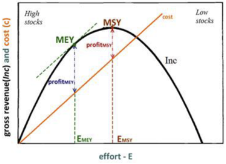
- At equilibrium $\pi(e) = ph(e) - ce$
- MEY: Optimal rent at equilibrium

$$\max_{e \geq 0} \pi(e)$$

- Logistic:

$$x_{\mathrm{MEY}} = \frac{k}{2} + \frac{c}{2pq}, \; e_{\mathrm{MEY}} = \frac{r}{2q}\left(1 - \frac{c}{pqk}\right)$$

- Stock economically overexploited if $e > e_{\mathrm{MEY}}$



Bio-economic synergies

$$x_{\mathrm{MEY}} > x_{\mathrm{MSY}}$$

Optimal control approach

Conrad-Clark, 1987; DeLara-Doyen, 2008

We consider the dynamic optimization problem

$$\max_{h(0),h(1),\ldots} \sum_{t=0}^{\infty} (1+\rho)^{-t} \pi(x(t), h(t))$$

under the renewable resource dynamics

$$x(t+1) = x(t) + G(x(t)) - h(t) .$$

Discounted MEY

Using Hamiltonian and maximal principle, discounted MEY x_∞

Conrad-Clark, 1987; DeLara-Doyen, 2008

$$\rho = G'(x_\infty) + \frac{\pi_x(x_\infty, G(x_\infty))}{\pi_h(x_\infty, G(x_\infty))}$$

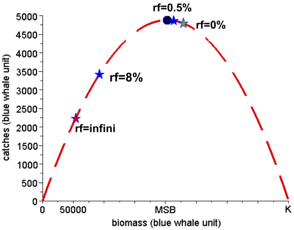
Blue whale (Kot, 2001)

$k = 400000$ $r = 5\%$ $q = 0.0016$

$c = 60000$ $p = 7000$

MEY and OA as particular cases:

- $\rho = 0$: $x_\infty \to x_{\mathrm{MEY}}$
- $\rho = \infty$: $x_\infty \to x_{\mathrm{OA}}$



Long term equilibrium x_∞

Where extinction is optimal I

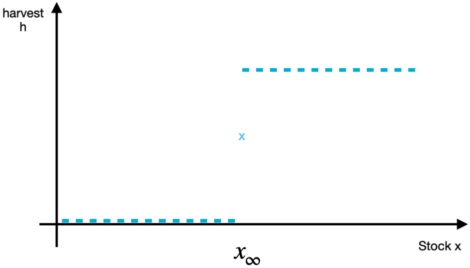
Let us consider the illustrative case where

- Logistic dynamics
- rent is of the form $\pi_x = 0$

Result: Then if $r \leq \rho$ then extinction is optimal $x_\infty \leq 0$.

More general conditions in Clark (1990), Grafton et al. (2010)

Concern in terms of intergenerational equity



Close the fishery if the initial stock is low !!!! Social concerns

Extension of MSY to multispecies: MMSY

Legovic et al., Ecol. Mod., 2010; Tromeur & Doyen, ENMO, 2018

Multi-species dynamics

$$x_i(t+1) = x_i(t)\left(1 + r_i\left(1 - \frac{x_i(t)}{k_i}\right) - q_i e(t)\right)$$

Equilibria:

$$x_i(e) = k_i\left(1 - \frac{q_i}{r_i} e\right)$$

MMSY objective

$$\max_{e \text{ at equilibrium}} \sum_i h_i(e, x_1, \ldots, x_n) = \max_e \sum_i q_i x_i(e) e$$

We obtain

$$e_{MMSY} = \frac{1}{2\sum_i \frac{q_i^2 k_i}{r_i}} \sum_i q_i k_i$$

Where extinction is optimal II

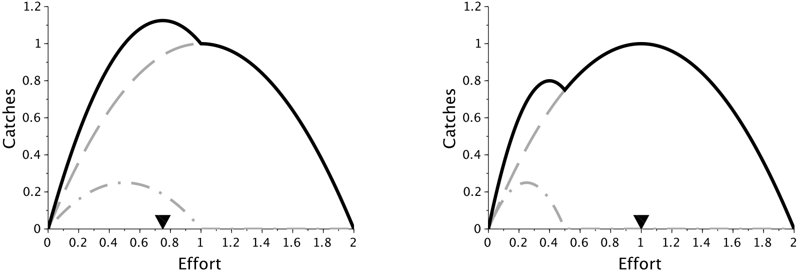
Compare e_{MMSY} with $e^i_{\mathrm{MSY}} = \frac{r_i}{2q_i}$, $x^i_{\mathrm{MSY}} = \frac{k_i}{2}$,
Examples with 2 species

- $r_1 = 2,\ r_2 = 1,\ q_1 = q_2 = 1,\ k_1 = 2,\ k_2 = 1$: we obtain

  species 2 overexploited

- $r_1 = 2,\ r_2 = 0.5,\ q_1 = q_2 = 1,\ k_1 = 2,\ k_2 = 1$: we obtain

  species 2 extinct



Where extinction is optimal III in multi-species context and optimal control

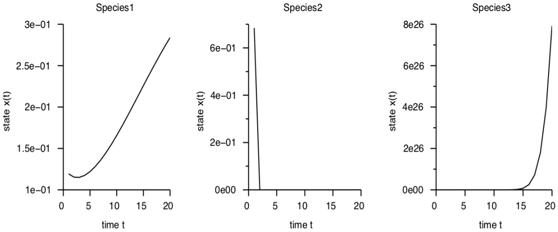
Fischer- Mirman, JEEM, 1996

Doyen et al., Dynamic Games and App., 2016

Result: The optimal harvest for every species i

$$h_i^* = \frac{\beta_i}{\beta_i + \rho\left(\left(I+S\right)' w\right)_i} x_i$$

If $((I+S)'w)_i = 0$ then species i collapses

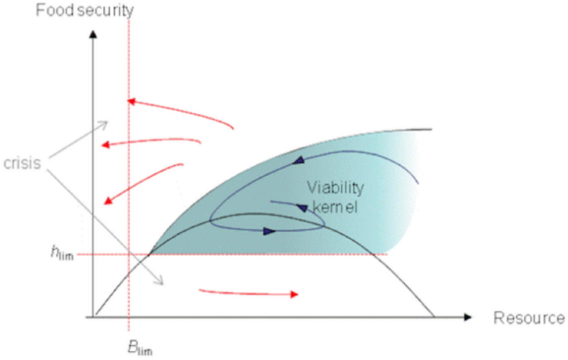


Viable control approach

Aubin., SICON, 1991, *Bene et al., Ecological Economics, 2001*

Schuhbauer & Sumaila, 2016, *Oubraham & G. Zaccour, 2018*

Sustainability of dynamic systems through constraints and thresholds



Viability= Catenaccio

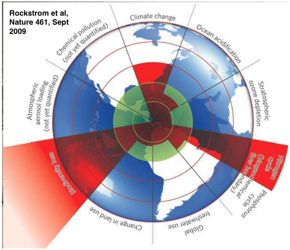
Catenaccio

is a tactical system in football with a strong emphasis on defence. In Italian, catenaccio means "door-bolt", which implies a highly organized and effective backline defence focused on nullifying opponents' attacks and preventing goal-scoring opportunities.

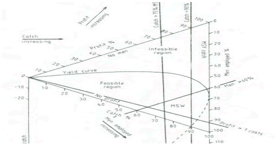
Links with other approaches for sustainability

Doyen, Armstrong, Baumgartner et al., Ecological Economics, 2019

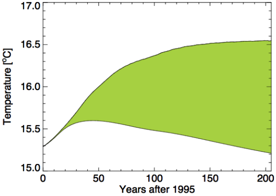
SOS



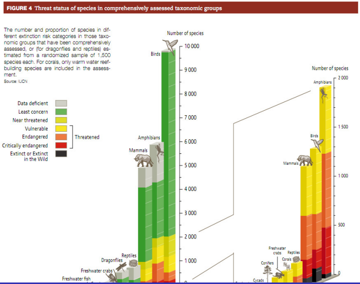
Minimal Sustainable Whinge



TWA



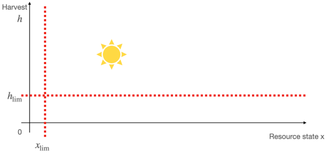
PVA



Eco-viability for a stylized bio-economic model

Béné-Doyen-Gabay, Ecological Economics, 2001

- A population dynamics
$$x(t+1) = x(t) + G(x(t)) - h(t)$$
- A conservation requirement:
$$x(t) \geq x_{\lim},$$
- An ecosystem service requirement:
$$h(t) \geq h_{\lim}$$
- The field of possibilities: the viability kernel

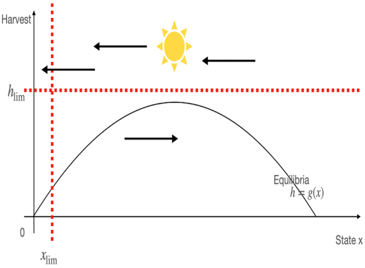


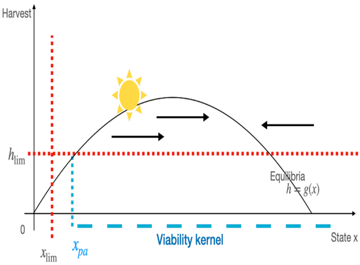
$$\mathrm{Viab} = \left\{ x_0 \;\middle|\; \begin{array}{l} \exists\ h(t) \text{ and } x(t) \text{ starting from } x_0 \\ \text{satisfying dyna. } + \text{ constraints} \\ \text{for any time } t \in \mathbf{R}^+ \end{array} \right\}$$

The field of possibilities I: Viable states

Doyen L. , Armstrong C., Baumgärtner S. et al. (2019)

Assume $g_x > 0$; $G(0) = 0$; $G(k) = k$; $g_{xx} < 0$





$$\mathrm{Viab} = \emptyset$$

- If $h_{\lim} > h_{\mathrm{MSY}}$

$$\mathrm{Viab} = [x_{\mathrm{pa}}, +\infty[$$

- if $0 \leq h_{\lim} \leq h_{\mathrm{MSY}}$
- The precautionary threshold

$$x_{\mathrm{pa}} = \min\Big(x,\ G(x) = h_{\lim}\Big)$$

The field of possibilities II: The viable catches:

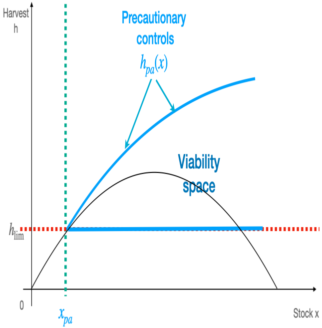
Method: Maintaining x in Viab

Viable quotas:

$$[h_{\lim}, h_{\mathrm{pa}}(x)]$$

where

$$h_{\mathrm{pa}}(x) = h_{\lim} + x - x_{\mathrm{pa}} + G(x) - G(x_{\mathrm{pa}})$$



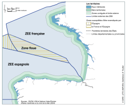
Different strategies:

- Conservative $h_{\lim}$
- Greedy $h_{\mathrm{pa}}(x)$
- Trade-off: $\alpha h_{\lim} + (1-\alpha) h_{\mathrm{pa}}(x)$
- MSY, MEY, ...

A stylized example: nephrops fishery in Bay of Biscay

Martinet-Thébaud-Doyen, Ecological Economics, 2007

Funding ANR Chaloupe



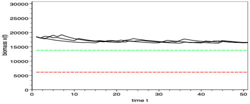
- Logistic Dynamics: $r = 1.78, \; k = 30800$
- Constraints of eco-viabiliy:

$$\pi(x(t), h(t)) \geq \pi_{\lim}, \; x(t) \geq x_{\lim}$$

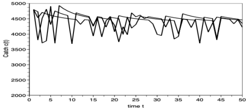
$p = 8500$ €$.ton^{-1}$, $c = 377$ €$.day^{-1}$, $q = 72{*}10^{-7}\ day^{-1}$.

- Viability kernel:

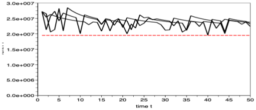
$$x \geq x_{pa}$$



Stock $x(t)$



Catch $h(t)$



Profit $\pi(t)$

Other applications of viable control approach

Many examples now worldwide

(Schuhbauer & Sumaila, Ecol Econ. 2019; Oubraham & Zaccour, 2020) ....

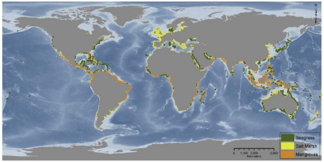


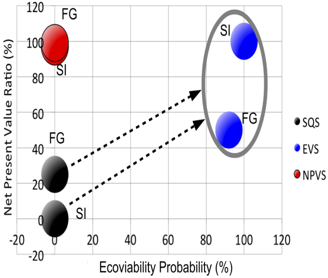
Figure 1. Global distribution of seagrasses, tidal marshes, and mangroves. Data sources: Seagrass and saltmarsh coverage data are from the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC); mangrove coverage data are from UNEP-WCMC in collaboration with the International Society for Mangrove Ecosystems (ISME).
doi:10.1371/journal.pone.0043542.g001

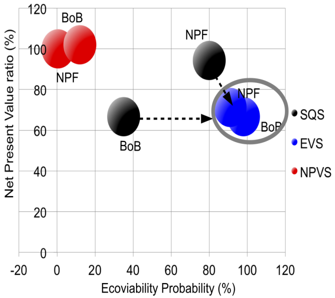
- **Australia**: Gourguet al, Fish. Res. (2013), Thebaud et al, Ecol. Ind. (2014); Tromeur et al, Ecol. Econ. (2019), Briton et al, ENMO (2020)
- **NZ**: Krawczyk et al. (2013) Comp. Manag. Sci.
- **Pacific Islands**: Doyen et al., Ecol Mod., (2007); Hardy et al. 2013 (EDE); Hardy et al., 2017; Lagarde, PhD
- **Peru - Chile**: DeLara et al., ENMO, (2012); Gajardo, ENMO (2018).
- **French Guiana**: Cissé et al., Ecological Economics, 2013, 2015; Gomes et al, ENMO, 2021; Cuilleret et al., EAP, 2022; Kersulec et al., ENVI, 2024
- **Spain**: Maynou et al, Marine Sciences, 2015
- **Bay of Biscay**: Doyen et al, EE, 2012; Gourguet al, FF, 2014; ....

but not enough **theory** for multi-species and **spatially explicit models**

Comparative analysis between case-studies

FG: French Guiana; NPF: Australian Northern Prawn;
SI: Solomon Islands; BoB: Bay of Biscay





a) Small scale fisheries
Win-Win viability - optimality

b) Large scale fisheries
Trade-off viability - optimality

Maximin and viability

Doyen-Martinet, JEDC, 2012; Martinet-Doyen, REE, 2007

- Maximin : a pessimistic approach

  Rawls (1971), Solow (1974), Cairns & Long (2006)

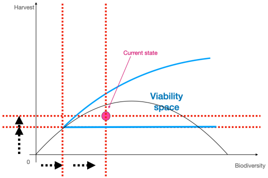
$$V^*(x_0) = \max_{e(.)} \min_{t=0,..,T} \pi(x(t), e(t))$$

- Result: Maximin = **maximal viability**:

$$V^*(x_0) = \max\left(\pi_{\mathrm{lim}} \middle| \, x_0 \in \mathrm{Viab}(\pi_{\mathrm{lim}})\right)$$

where $\mathrm{Viab}(\pi_{\mathrm{lim}})$ the viability kernel with

$$\pi(x(t), e(t)) \geq \pi_{\mathrm{lim}}$$



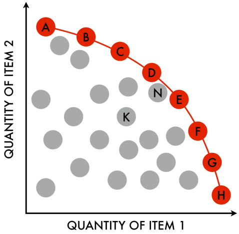
- Intergenerational equity in viability

Doyen & Gajardo, Natural Resource Modeling (2021)

- Multi-criteria maximin ?

$$\mathcal{V}^*(x_0) = \max_{decisions} \left(\min_t \pi_1(t), \ldots, \min_t \pi_m(t) \right)$$

- Result: Multi-criteria Maximin : **maximal (Pareto) viability**



$$\begin{aligned} \mathcal{V}^*(x_0) &= \max \left(\pi_1^{\lim}, \ldots, \pi_m^{\lim}\right) \mid x_0 \in \mathrm{Viab}(\pi^{\lim}) \\ &= \mathcal{P}areto\ boundary\left(\mathcal{S}ust(x_0)\right) \end{aligned}$$

where $\mathcal{S}ust(x_0)$ sustainability thresholds from x_0 = **inverse viability** set as

$$I^{\lim} \in \mathcal{S}ust(x_0) \Leftrightarrow x_0 \in \mathrm{Viab}(I^{\lim}).$$

Application to renewable resource management

Dynamics in discrete time:

$$x(t+1) = x(t) + G(x(t)) - h(t)$$

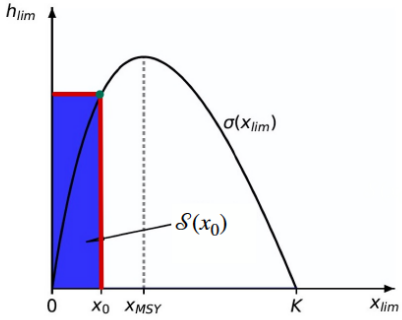
where

- $x(t)$ biomass or abundance
- $h(t)$ catches

Multi-criteria maximin ?

$$\max_{(x(\cdot),h(\cdot))} \left(\min_t x(t), \min_t h(t) \right)$$

Catch vs conservation



Strong Pareto maximin boundary

$$\mathcal{V}^*(x_0) = \begin{cases} (x_0, G(x_0)) & \text{if} \quad x_0 \leq x_{msy} \\ \{(x, G(x)) \mid \ x_{msy} \leq x \leq x_0\} & \text{if} \quad x_{msy} \leq x_0 \leq K \end{cases}$$

For stocks at risk, win-win conservation and sustainable yield !!!

Conservation versus Profitability

Dynamics in discrete time:

$$x(t+1) \quad = \quad x(t) + G(x(t)) - qe(t)x(t)$$

where $e(t)$ effort

Equilibrium:

$$\sigma(x) = \left(p - \frac{c}{qx}\right) G(x)$$

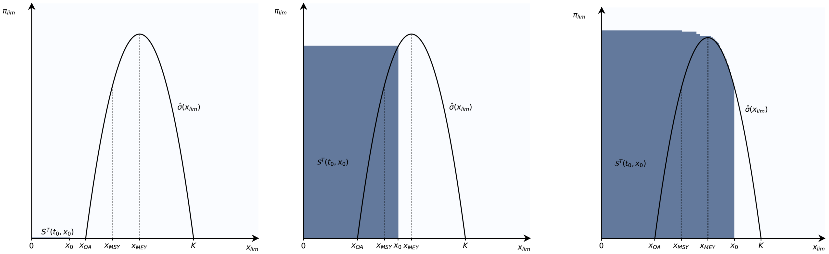
Profit:

$$\pi(x(t), e(t)) = pqe(t)x(t) - ce(t)$$

Multi-criteria maximin ?

$$\max_{(x(\cdot),e(\cdot))} \left(\min_t x(t), \min_t \pi(t)\right)$$

Conservation vs Profit



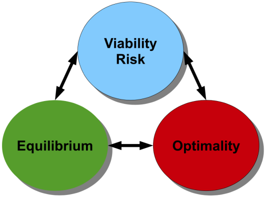
Pareto maximin

$$\mathcal{V}^*(x_0) = \begin{cases} (x_0, 0) & \text{if} \quad x_0 \leq x_{\mathrm{OA}} \\ (x_0, \sigma(x_0)) & \text{if} \quad x_{\mathrm{OA}} \leq x_0 \leq x_{\mathrm{MEY}} \\ \{(x, \sigma(x)) \mid \; x_{\mathrm{MEY}} \leq x \leq x_0\} & \text{if} \quad x_{\mathrm{MEY}} \leq x_0 \leq K \end{cases}$$

For stocks at risk, win-win conservation and sustainable profitability !!!

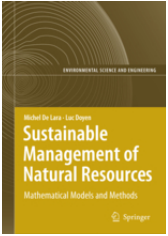
To conclude

- **Interest of maximin and viability approach** for strong sustainability: dynamic, multi-criteria, equity.
- However **many links between approaches** of sustainability



- Need to **connect theory and applications**
- **Challenges**:
  - EBFM with Maximin, Viability, Optimality under constraints
  - Sustainable Seafood Systems with Maximin, Viability, ..
  - Account for uncertainties: resilience criteria and strategies

Some references



- Baumgartner S., Quaas M.F., 2009, Ecological-economic viability as a criterion of strong sustainability under uncertainty, Ecological Economics, 68 (7), 2008?2020.
- Doyen L. , Armstrong C., Baumgärtner S. et al. (2019) From no whinge scenarios to viability tree, Ecological Economics. https://www.sciencedirect.com/science/article/pii/S0921800918301824
- Cissé et al (2013) A bio-economic model for the ecosystem-based management of the coastal fishery in French Guiana, Environmental and Development Economics.
- Doyen et al (2013). Ecological-economic modelling for the sustainable management of biodiversity, Computational Management Science.
- Krawczyk J. et al. , 2013, Computation of viability kernels : A case study of by-catch fisheries, Computational Management Scienc, pp. 1-32.
- Mouysset et al (2014), Co-viability of farmland biodiversity and agriculture, Conservation Biology.
- Péreau et al (2012) The triple bottom line: Meeting ecological, economic and social goals with ITQ's, J. of Environ. Econ. and Management.
- Gourguet S. et al., 2013, Managing mixed fisheries for bio-economic viability, Fisheries Research, 140, 46-62.
- Hardy P.Y. et al.., 2013, Food security - environment conservation nexus: a case study of Solomon Islands' small-scale fisheries, Environmental Development
- Doyen L. et al. 2012, A stochastic viability approach to ecosystem-based fisheries management, Ecological Economics
- K. Eisenack et al. (2006): Viability Analysis of Management Frameworks for Fisheries. Environmental Modelling and Assessment, 1, 1, 69-79.
- Doyen L., Martinet V., 2012, Maximin, Viability and Sustainability, Journal of Economic Dynamic and Control

Man

versus Fish

Humans vs Nature

Fisheries are a paradigmatic example of interaction between an ecological system and human societies.

- ecological systems are described by their biophysical dynamics, modelled by deterministic or stochastic differential equations
- humans have, or claim to have, rationality: they have a purpose for whatever they do, and they strive to achieve it.

So we need an added modelling tool for humans. In the past hundred years, this has been optimization . It is used:

- in economics, to model individual and collective goals
- in finance, where the objective is profit

The biophysical model

We shall take a very simple one:

$$\frac{dx_t}{dt} = G(x_t) - h_t$$

. This is supposed to model a fishery, with $x_t \geq 0$ is the stock, and $h_t \geq 0$ the catch at time t. A standard specification is

$$G(x) = rx\left(1 - \frac{x}{K}\right)$$

More sophisticated models are possible, but would obscure our argument. Note that such models come with biophysical boundaries:if they are crossed, the system dies or fundamentally changes. Here $x \geq 0$, or $x \geq x_{\mathrm{low}} > 0$ (Allee effect)

Human activity

Humans act on the ecosystem by catching fish (among others).The problem is to understand this activity, and if possible to make it compatible with the survival of the ecosystem: h_t should be such that x_t stays within the biophysical boundaries. This is the purpose of the viability approach

Can we stay within the viability set ? With a globalized market economy and an neo-liberal economic theory, the operating principles for human activity are:

- collective motivation: fish should yield maximum welfare to humans
- individual motivation: individual fishermen should maximise profit

The basic tool is optimization: something should be maximised, either profit or some indicator of collective welfare

The unitary model

This model sweeps all difficulties under the rug. There is:

- a single actor, the planner (representing mankind)
- a single beneficiary, the consumer (representing mankind)
- a single good (fish) caught costlessly

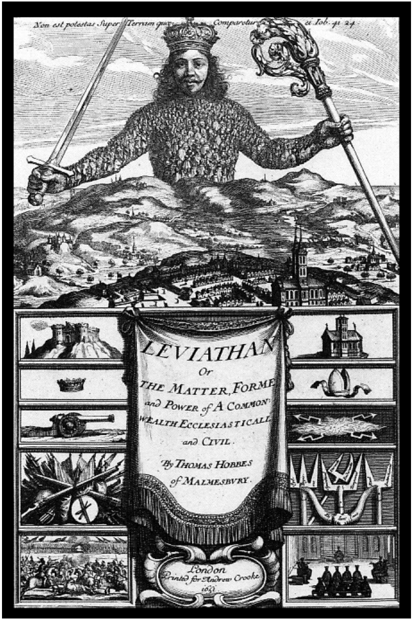
The welfare associated with consuming h_0 now is $u(h_0)$ and of consuming h_t at a later time t is $e^{-\rho t}u(h_t)$. The welfare from a flow $h_t,\ t \geq 0,$ is:

$$I_0(h) = \int_0^\infty e^{-\rho t} u(h_t)\, dt$$

Exploiting the fishery is represented by the optimisation problem:

$$\max_h I_0(h) \quad \frac{dx}{dt} = G(x) - h$$

Who optimizes ?



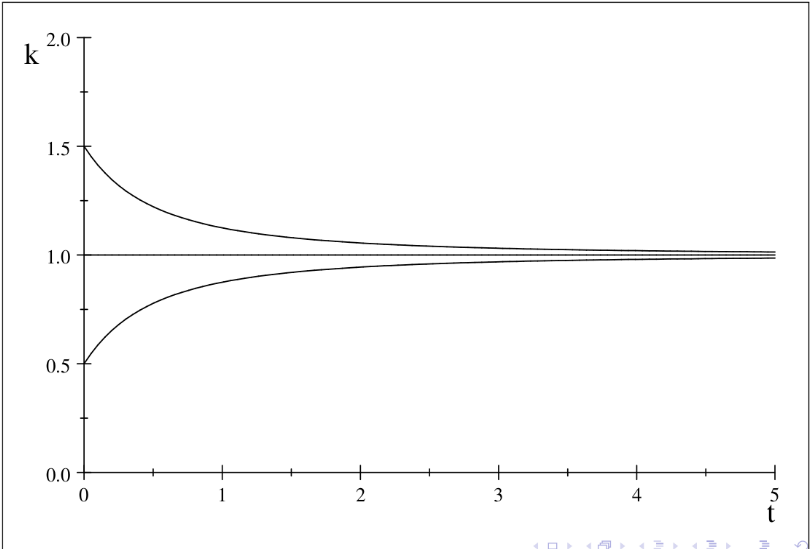
Solving the unitary model

The optimal strategy converges towards a stationary situation (x_∞, h_∞) defined by:

$$G'(x_\infty) = \rho, \quad h_\infty = G(x_\infty)$$

If ρ is too high, $G'(0) < \rho$, that is, if the planner is impatient then the fish are driven to extinction. Note that this does not depaend on the welfare indicator u : the planner may be greedy, but he/she should not be impatient

Optimal trajectories



Caring for the seventh generation: the Chichilniski model

There is more to fish than only eating it. Let $U(x)$ be the value of having the stock at the level x The planner then seeks

$$\max_{h} \left\{ \int_0^{\infty} e^{-\rho t} u\left(h_t\right) dt + \alpha U\left(x_{\infty}\right) \right\}$$

where $\alpha \geq 0$ measures the importance of the long-term stock.

- The *BAU* (Business as Usual) strategy maximises the first term. The stationary stock x_{BAU} is given by $F'\left(x_{BAU}\right) = \rho$
- The *NC* (No Catches) stragegy consists of not fishing, which maximises the second term. It leads to $x = K$

Maximising them independently we get an upper bound

$$I = \alpha U\left(K\right) + \max_{h} \int_0^{\infty} e^{-\rho t} u\left(h_t\right) dt \tag{1}$$

When optimising has no bite

There is no optimal strategy . Indeed I cannot be achieved, but can be approximated as closely as we want by applying BAU until time T and then switching to NC

The larger T the closer is the strategy to the optimum: one always improves the criterion by postponing the time when one switches to NC. The search for optimisation leads to procrastination: it is always to early to switch, so switching never occusrs, and in practice the BAU strategy is applied

Executable strategies

If the initial state x_0 is larger than $x_{BAU,}$ there is an interesting class of (non-optimal) strategies. Fix x_1 between x_0 and x_{BAU} and consider the optimisation problem:

$$\max_h \int_0^\infty e^{-\rho t} u(h_t)\, dt \qquad (2)$$

$$\frac{dx}{dt} = F(x) - h, \quad x(0) = x_0, \quad \lim_{t\to\infty} x(t) = x_1 \qquad (3)$$

It turns out that this problem has an optimal solution, and that if x_1 is close enough to x_{BAU} the corresponding strategy σ has th property that small deviations are penalized: changing h between t and $t+\varepsilon$ and reverting to σ after that decreases the payoff. Such strategies are called *executable*

Intergenerational equity: the Sumaila-Walters model

There is a total population N which is constant through time, but contains successive generations. Let n be its rate of renewal, meaning that $nNdt$ individuals die and $nNdt$ are born between t and $t + dt$.

The fish is a common good between all generations, and should be shared fairly. The planner gives a weight $e^{-\delta t}$ to the generation born at time t, which leads to the criterion:

$$I_0(h) + \int_0^{\infty} e^{-\delta t} I_t(h)\, n dt$$

where $I_t(h) = \int_t^{\infty} e^{-\rho(s-t)} u(h_s)\, ds$ is the utility at birth of the generation born at time t

Caring for future generations

The criterion to be optimized becomes:

$$I(h) = \int_0^{\infty} R(t)\, u(h(t)dt \tag{4}$$

where the discount factor $R(t)$ is given by:

$$R(t) = \lambda e^{-\rho t} + (1-\lambda)\, e^{-\delta t} \tag{5}$$

$$\lambda = \left(1 + \frac{n}{\delta - \rho}\right), \quad \delta > \rho \tag{6}$$

Note that this corresponds to a non-constant discount rate $r(t)$

$$r(t) := -\frac{R'(t)}{R(t)} = \frac{\lambda\rho - (\lambda-1)\,\delta e^{(\rho-\delta)t}}{\lambda - (\lambda-1)\, e^{(\rho-\delta)t}}$$

$$r(t) \longrightarrow \rho - n \quad \text{when} \quad t \longrightarrow 0$$

$$r(t) \longmapsto \rho \quad \text{when} \quad t \longrightarrow \infty$$

It turns out that, like the Chichilnisky model, the Sumaila-Walters model admits no optimal solution. But the reason is different: because of the non-constant discount rate, a flow h which is optimal for the present generation will not be so for later ones. So the present generation is in a quandary: how can it plan for future catches when it knows that future generations will not apply the plan ?

So the emphasis shifts from optimal strategies to executable strategies, i.e. a strategy that every generation will follow, provided the following ones do.

We try a formal definition. Consider Markovian strategies $h = \sigma(x)$and the corresponding dynamics

$$\frac{dk}{dt} = f(x) - \sigma(x)$$

Executable strategies

A strategy σ is announced. At time T the stock is x_T, and the planner considers what she is to do now, i.e. in the interval $[T,\ T+\varepsilon]$, $\varepsilon \to 0$. She can:

- either apply σ, catch $h = \sigma(x_T)$ leading to:

$$I_T = \int_T^{\infty} R(t-T)\,\sigma(x_t)\,u(ht))dt$$

- or catch $h \neq \sigma(x_T)$, between T and $T+\varepsilon$ and revert to σ afterwards. Denote by $I_T(\varepsilon, h)$ the resulting welfare

Definition

The Markovian strategy σ is executable if :

$$\lim_{\varepsilon\to 0} \frac{1}{\varepsilon}\left[I_0 - I_T(\varepsilon, c)\right] \leq 0 \quad \text{pour tout} \quad c \quad \text{et} \quad T$$

From the point of view of game theory, this is a Nash equilibrium between generations: unilateral deviations are penalized

What do they look like ?

Recall the Sumaila-Walters criterion

$$\int_0^\infty \left(\lambda e^{-\delta t} + (1-\lambda)\, e^{-\rho t}\right) u\,(c)\, dt, \quad c \in \mathcal{A}\,(k_0)$$

Define two points x_h et x_ℓ par:

$$\begin{aligned} f'\,(x_\ell) &= \delta + (1-\lambda)\,\rho \\ f'\,(x_h) &= \left(\frac{\lambda}{\delta} + \frac{1-\lambda}{\rho}\right)^{-1} \end{aligned}$$

Theorem

For every x_∞ between k_ℓ and k_h there exists an equilibrium strategy k_∞

Example: the Gordon-Schaefer model

There is a financial market where the unique actor can borrow and lend money costlessly at the interest rate and a market for fish where he/she can sell the catch at (fixed) price p. He/she seeks to maximise profit:

$$u(h) = ph - c(x)h$$

where the last term is the cost of catching h when the stock level is h. The discounted profit to be maximised is:

$$\int_0^{\infty} e^{-\rho t} (ph - c(x)h)\, dt$$

One converges to a stationary situation (x_∞, h_∞) defined by:

$$F'(x_\infty) - \frac{F(x_\infty)c'(x_\infty)}{p - c(x_\infty)} = \rho$$

It can be proved that if the price is high enough, $p \geq c(0)$, and the interest rate is high enough, $\rho > 2F'(0)$. it is financially optimal to drive the fishery to extinction

Intergenerational equity for fisheries

The criterion to be optimized becomes:

$$I\left(h\right)=\int_{0}^{\infty}R\left(t\right)\left(p-c(x(t))\right)h(t)dt \tag{7}$$

There is a unique executable strategy, leading to a stationary population, given by:

$$F'\left(x_{\infty}\right)-\frac{F\left(x_{\infty}\right)c'\left(x_{\infty}\right)}{p-c\left(x_{\infty}\right)}=\rho-n$$

where is the interest rate, and n is the rate of renewal of the (presumed constant) human population. Note that it does not depend on δ, the relative weight given to future generations! So taking into account future generations in Gordon-Schaefer amounts to lowering the interest rate by n, the renewal rate, which will increase the stationary stock level

Conclusion

- framing the exploitation of fisheries as an optimisation problem is extremely restrictive: it sweeps under the rug most problems, such as intra- and intergenerational equity, which are best understood as (cooperative and non-cooperative) games
- biophysical constraints (viability) must be taken explicity into account, they will not arise naturally from the optimisation procedure or the search for Nash equilibria
- it is much easier to prevent the stock level from falling below a certain limit than to rebuild a stock to former values
- taking into account the interests of future generations in Gordon-Schaefer is easy and leads to increasing stock levels